

Explosion-Induced Combustion of Hydrocarbon Clouds in a Chamber

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Extended Abstract for the
**18th International Colloquium on the
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Abstract. The interaction of the detonation of a solid HE-charge with a non-premixed cloud of hydro-carbon fuel in a chamber was studied in laboratory experiments. Soap bubbles filled with a flammable gas were subjected to the blast wave created by the detonation of PETN-charges ($0.2 \text{ g} < \text{mass} < 0.5 \text{ g}$). The dynamics of the combustion system were investigated by means of high-speed photography and measurement of the quasi-static chamber pressure.

Experimental Setup. The experiments summarized here were carried out in a rectangular chamber shown in Fig. 1. The chamber has inner dimensions of 101.5 mm x 101.5 mm x 386 mm. Floor, roof and the end walls were manufactured from 10-mm thick steel and equipped with fixtures used to either install piezo-electric or piezo-resistive pressure gages or to hold a bubble generator or the charge mount. The side walls allowed for optical access, being manufactured from 10-mm thick Makrolon, a transparent polycarbonate.

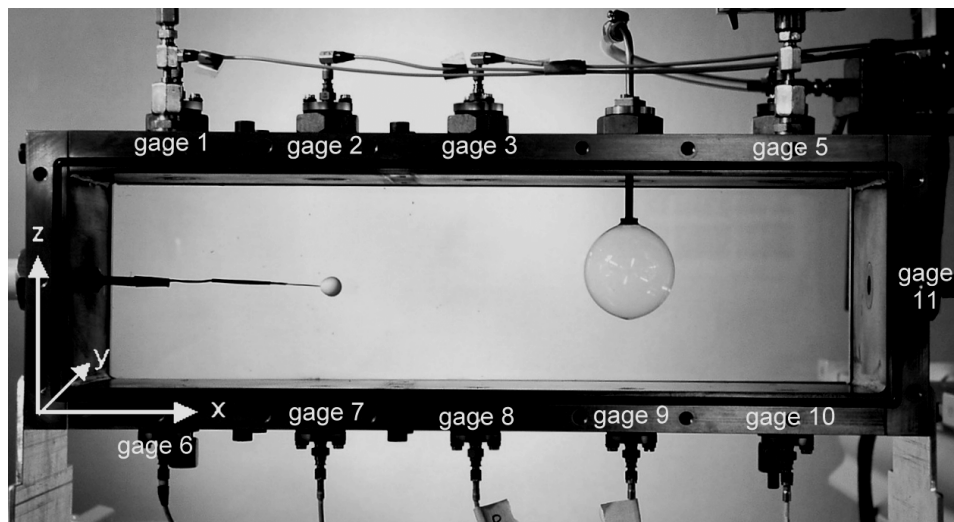


Fig. 1 Picture of the set-up. Front and back walls (Makrolon) are removed for the photograph. Below gage 2 a 0.5-g PETN-charge is centered in the model at $x = 96.5 \text{ mm}$. The bore hole for gage 4 holds the muzzle of the bubble generator. The bubble (here air-filled) is located at $x = 268 \text{ mm}$ and its diameter is about 50 mm.

To prevent pre-mixing with the ambient air, the hydro-carbon cloud was contained in a soap-bubble located at $x = 268$ mm. Most tests were conducted with a bubble diameter of 50 mm, which yields a bubble volume of about 66 ml in comparison to the chamber volume of 3.98 l. Three different test gases have been investigated: acetylene (C_2H_2), propane (C_3H_8) and butane (C_4H_{10}). This report focusses on the results for butane.

The bubbles were exposed to the blast wave generated by the detonation of spherical PETN-charges ($0.2\text{ g} < \text{mass} < 0.5\text{ g}$). These were installed at various distances from the soap bubble, typically on the central axis of the chamber.

The main diagnostics were wall pressure gages to characterize both the blast environment and the development of the quasi-steady pressure in the chamber, shadow photography to visualize the blast propagation and a high-speed video camera and a photo-diode to monitor luminous phenomena in the chamber.

Experimental Findings. Figure 2 gives examples of overpressure-time histories measured in the experiments. It shows the readings from gage 11, a piezo-resistive gage in the end-wall of the chamber nearest to the gas cloud. Each plot compares a reference test (without a combustible gas cloud, black curve) to a test where the detonation ignited a butane cloud (red curve). In all three tests combustion increases the quasi-static overpressure by about 3 to 4 bars, though the increase develops at different times and with different rates.

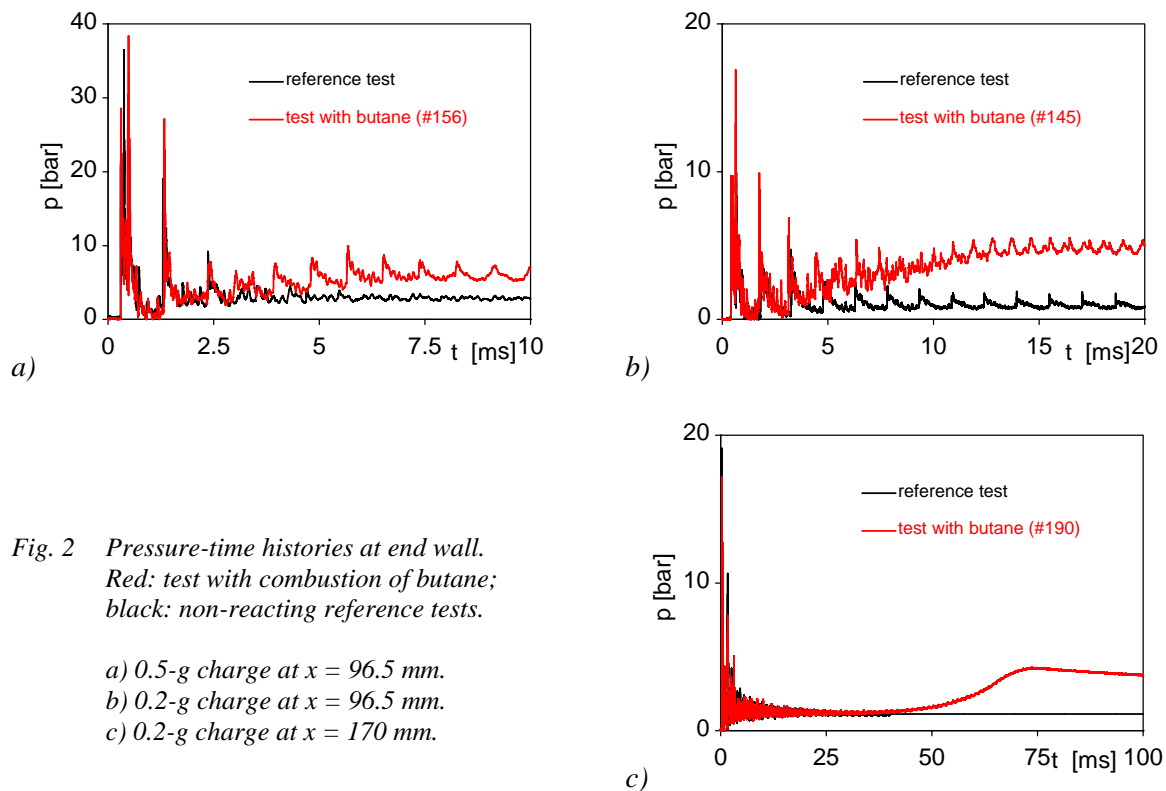


Fig. 2 Pressure-time histories at end wall.
Red: test with combustion of butane;
black: non-reacting reference tests.

- a) 0.5-g charge at $x = 96.5$ mm.
- b) 0.2-g charge at $x = 96.5$ mm.
- c) 0.2-g charge at $x = 170$ mm.

This combustion-induced increase which we term gain (in quasi-static overpressure) is closely related to the mass fraction burned, and its rate of change to the burning rate. Thus we employ it as the main quantitative means to characterize combustion effects.

Figures 4 to 8 display smoothed¹⁾ gain and rate curves for various charge masses and locations. For a charge of 0.5 g the current results indicate a 100%-probability that the detonation products will initiate combustion of the butane. The gain curves in Fig. 4 (each an average of two tests) compare well for different charge locations, starting with similar slopes and peaking between 6 and 7 ms after the detonation at gain values between 3 and 3.5 bar. The corresponding plot of the rate curves have somewhat more scatter due to the differentiation involved. We find maximum values for the rate of 0.8 to 1 bar/ms.

For a smaller charge mass of 0.3 g the gain curves (Fig. 5 displays averages of three tests each) exhibit larger differences with respect to the charge location. In addition, peak values occur later (note the changed scaling of the abscissa) at around 12 to 15 ms and the pressure rise is slower (maximum rates around 0.35 to 0.55 bar/ms).

When we reduce the charge mass to 0.2 g the overall probability of detonation-induced ignition drops to 48% (10 tests out of 21 exhibited combustion). The details strongly depend on the charge location (see Fig. 3).

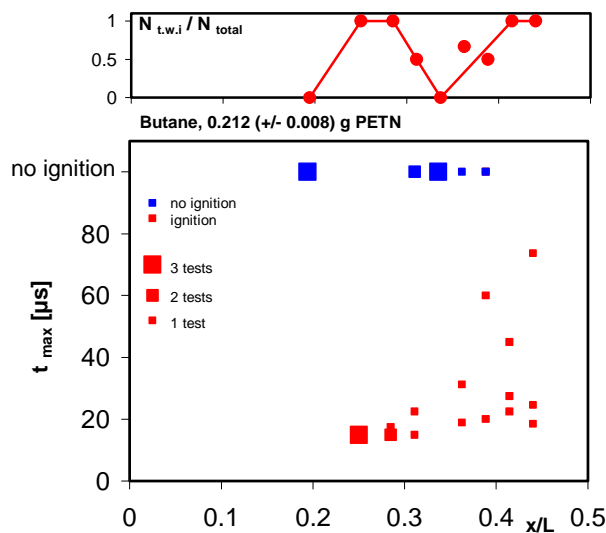


Fig. 3 Findings for 50-mm butane bubbles subjected to 0.2-g charges.
Upper part: Ignition probability vs. charge location (scaled with chamber length L).
Lower part: Scatter plot of the instant of maximum quasi-static overpressure.

The ignition probability varies with the charge position. Charges at $x = 75$ mm and at $x = 130$ mm repeatedly failed to cause combustion. Charges at $x = 96.5$ mm and 110 mm in contrast led to ignition and fairly reproducible gain curves. Other charge locations closer to the bubble caused a lot of scatter which is illustrated in the lower part of Fig. 3 showing a plot of the instants of maximum gain versus the charge location. The maximum quasi-static overpressure can be attained as late as 75 ms after the detonation (see also Fig. 2 c); but for the same parameter settings it may as well occur much earlier. The variety of gain and rate curves for the case of 0.2-g charges is exemplified in Fig. 6.

Fig. 7 compares sample gain curves for the three different charge masses. For each mass, an example which exhibits the steepest rise was chosen. Fig. 8 supplements a comparison of rate curves; here the selection was based on the earliest occurrence of the rate maximum. This comparison shows that the 0.2-g charges essentially continue the trend found for the difference between 0.5-g and 0.3-g charges: the gain curves peak later and rise with a smaller slope.

¹⁾ The gain curves, i.e., the differences between the signals from a test with combustion and a corresponding reference test, have to be strongly smoothed to suppress noise. The noise only in part originates from the limited reproducibility of the detonation. The combustion itself contributes to the noise as well since it increases the temperature in the chamber and thus modifies the propagation of the reflected shocks. In consequence the correlation between the shock signatures of the test with reaction and the reference test decreases with time, thus adding considerable "noise" to the difference.

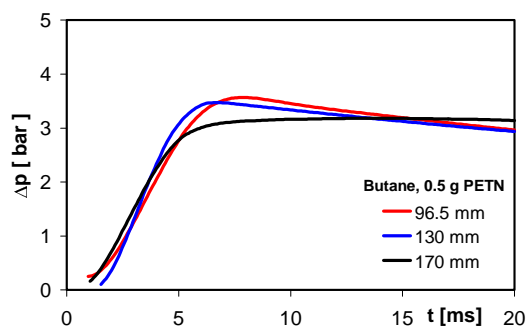


Fig. 4 a) Average gain curves for 0.5-g charges.

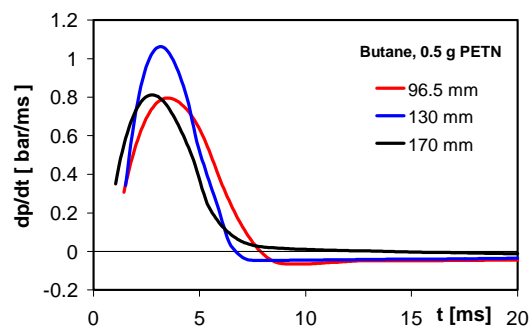


Fig. 4 b) Corresponding rate curves.

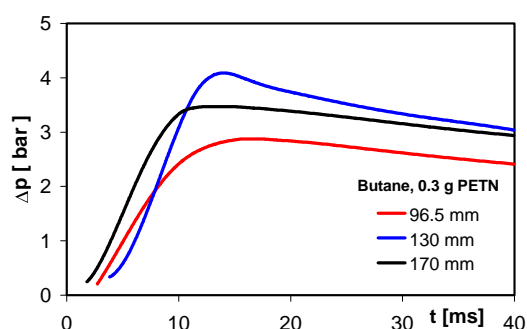


Fig. 5 a) Average gain curves for 0.3-g charges.

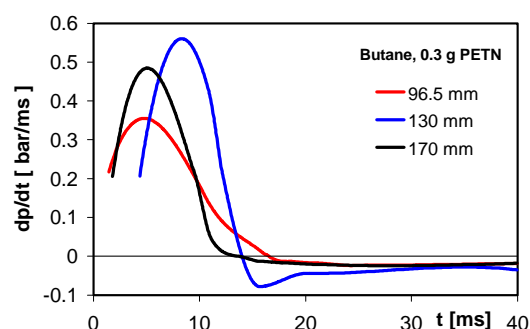


Fig. 5 b) Corresponding rate curves.

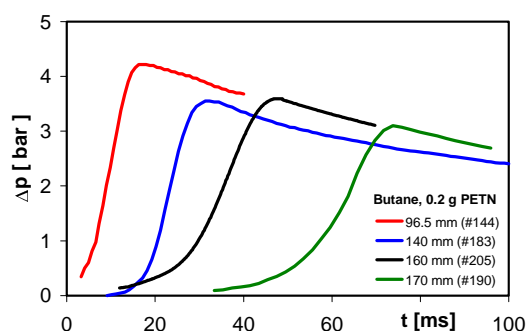


Fig. 6 a) Gain curves for four selected tests with 0.2-g charges.

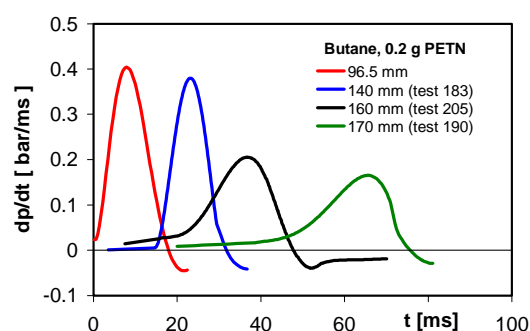


Fig. 6 b) Selected rate curves for 0.2-g charges. (Red: average of 3 tests, other: individual tests).

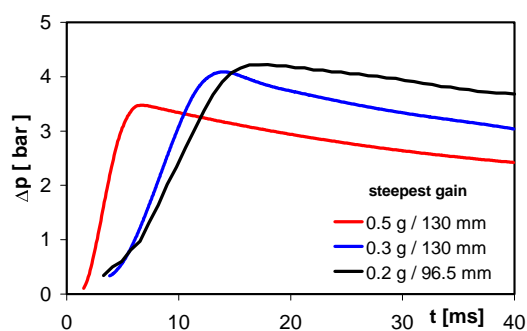


Fig. 7 Selected gain curves for different charge masses. (Criterion: steepest slope).

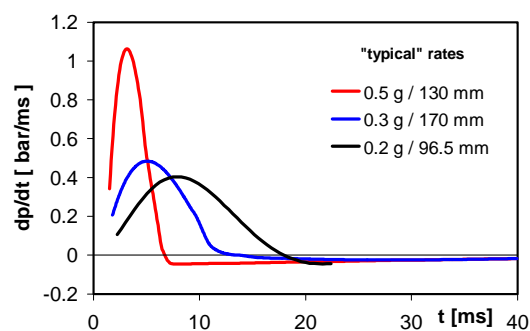


Fig. 8 Selected rate curves for different charge masses. (Criterion: earliest peak).

Only a few tests with charges around 0.1 g have been performed up to now. These tests generally failed to cause ignition of the butane bubble. To give a preliminary summary for the influence of the charge mass on the combustion of 50-mm butane bubbles: in the investigated range a critical threshold seems to exist which has to be exceeded to ensure ignition. In the current geometry this threshold value lies between 0.2 and 0.3 g PETN. Above this threshold an increase of the charge mass apparently increases the combustion rate. The charge location is a second parameter that influences the results. This is clearly obvious for tests in the critical range just below the charge mass threshold, but the dependency still exists – though less pronounced – for charge weights above the threshold. In this range it becomes conspicuous for example by differences in the (apparent) instant for the onset of combustion, a phenomenon that we also found for tests with acetylene.

For 50-mm acetylene bubbles 0.2 g PETN are sufficient to ensure ignition. The instant when combustion effects become apparent, for example in the high-speed movies, varies with the charge location: for $x = 170$ mm it occurs at a time of approximately 0.5 ms, for $x = 130$ mm at a time of 4.5 ms and finally for $x = 96.5$ mm at a time around 2.4 ms.

These differences cannot be due to the change in the stand-off distance from the gas bubble, since the largest delay is found at the intermediate distance ($x = 130$ mm). In our opinion this is an effect due to the flow field in the chamber. The detonation causes a strong oscillatory flow in the chamber and details of the oscillation mode definitely depend on the location of the detonating charge.

Conclusions. Both charge mass and location have a strong influence onto the characteristics of the turbulent flow field in the chamber. Both affect the combustion as well. Thus it is most probable that the dependencies of the combustion effects from these parameters (increased rates, delays in ignition etc.) reflect dependencies from the flow field. At least in the case of a charge mass above the critical threshold value one can assume flow dynamics and especially turbulence to be governing the combustion processes. Hence we expect that the system can be reasonably simulated by the AMR-code utilizing the gasdynamic combustion model, that Kuhl et al. (1999) have successfully applied to the afterburning of TNT in closed vessels.

References

[Kuhl 1999] Kuhl, A.L., Ferguson, R.E., and Oppenheim, A.K., “Gasdynamics of Combustion of TNT Products in Air”, *Archivum Combustionis*, **19**:1-4, (1999), pp. 67-89.

Acknowledgment

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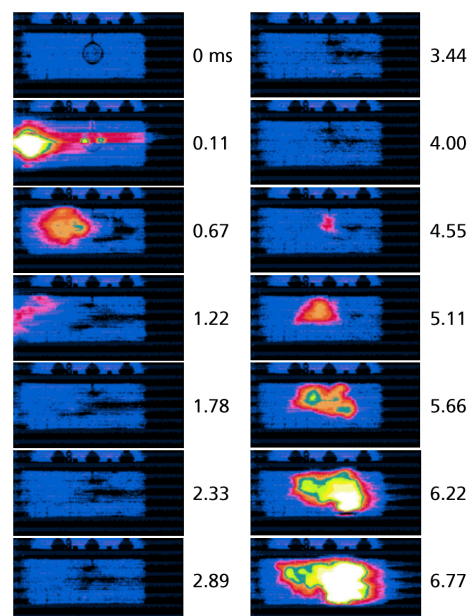


Fig. 9
Sequence of pseudo-color high-speed photographs depicting the hot detonation and combustion products in the chamber. Test conditions: 50-mm acetylene bubble subjected to a 0.2-g charge at $x = 130$ mm. With exception of black (setup contours) and blue (background) colors correspond to temperatures above approx. 700°C. At $t = 4.55$ ms we find the first indication of acetylene combustion (red cloud).